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M. M. Konyuk

X-RAY INVESTIGATION OF THE MECHANISM OF FATIGUE OF ANNEALED STEELS

The results of the works of various authors on the X-ray investigation of the mechanism of fatigue of metals and alloys are very contradictory. Therefore, there is a definite need for a more precise definition of certain questions characterizing the mechanism of fatigue and connected with the appearance of distortions of the crystal line structure during alternating deformation.

MATERIAL AND METHOD OF EXPERIMENT

The previously unstudied steel alloy 40X was used for the investigation. Since no dependence of mechanism of the fatigue process on the initial dimensions of the crystal line blocks has been revealed for any steel alloys, it was of interest to prepare crystal line blocks of various size in the annealed samples studied. Crystalline blocks with dimensions of the order of 10^{-3} and 10^{-5} cm were obtained at an annealing temperature of 800° C in vacuum for 2.5 hours and at 650° C for 2 hours, with subsequent cooling together with furnace.

The fatigue test was produced on the machine "NU." On standard samples, a hollow of radius r = 50 mm was bored out for predetermination of place of the break. Flat grooves were made along the holes, since an X-ray picture of a concave surface of small radius is accompanied by distortion of the shape of the lines. For determination of the fatigue limit, Veler curves were constructed; large block (10^{-3} cm) initial samples σ_s = 25.5 kg/mm^2; for samples with initial crystal blocks of the order of 10^{-5} cm, σ_s = 36 kg/mm^2. The fatigue tests were conducted at loads above and below the fatigue limit.

X-ray photography was carried out on the apparatus URS-50 I for ionization recording of the interference maxima and with use of the

tube BSVI in filtered iron radiation for I = 6 ma and U = 30 kv. The X -ray beam was limited by two slit diaphragms located between the X-ray tube and the samples, and a third with the filter in front of the counter. The X-ray interferences (110), (200), (211), (220) were determined for a time constant 3, the scale 1,000 pulses/sec. For the line (110) a correction was introduced for dead time of the counter. The line (220) was established also for a time constant of integration 4 and scale 200 pulses/sec. Such a choice of conditions of survey ensured large area both of the line (110), and of (220) and, consequently, a decreasing error in measurement of their areas and ordinates. The speed of goniometer was 1 deg/min. Every line was established three times in a large interval of angles. The reproducibility of the measurements for every line was to better than 2%. Construction of the distribution curve for the intensity from the line width was made from the points.

RESULTS OF EXPERIMENT

Because of the uncertainty of the existing methods of calculation of the average magnitude of mosaic blocks and micro-distortions, these methods were subjected to special investigation [1]. It turned out that integral methods, method of Kurdyumov--Lysak, the method of Hall and method of harmonic analysis of two lines of Khachaturyan give similar values for the relative magnitude of the crystal line blocks. For an increase of the line width (220) by a factor of two as compared to the line width for standard sample, but line (110)--by 1/3, the error in the determination of the relative magnitude of the crystal line blocks in one of the above-mentioned methods amounts to 5%. The determination of the line width was made by the method of Stokes. Separation of the K_{α} -doublet of line (220) was made by the method of Rechinger.

The results of measurement of line widths of (220) and (110) are given in Table 1 for samples having an initial magnitude of blocks of the order of 10^{-5} cm for loads 2 kg/mm^2 below the fatigue limit, at the fatigue limit and at 2 kg/mm^2 higher than this limit. The change of widths of the lines (220) and (110) takes place for all the loads considered. For a load 2 kg/mm^2 higher than the fatigue limit, large broadening of lines will appear.

For dangerous zone of load (higher than the fatigue limit), the change of the line widths of (200) and (110) ceases at 4×10^5 cycles, and at a load lower than fatigue limit and at fatigue limit--the change is cyclic at 6×10^5 cycles.

Separate determination of the effects of the second kind, carried out by the method of harmonic analysis of the two lines (200) and (110), allowed us to establish that in process of testing 40X steel for fatigue, a crushing of the blocks of the mosaic occurs. Growth of micro-distortions is not observed.

Table 1

Magnitude of Blocks of order 10^{-5} cm

a № образца	b Напряжение цикла, кг/мм²	c Число циклов	d $B_{(220)}$, мм	e $B_{(110)}$, мм
10 f (стандартный образец)	0	0	1.23	0.75
91 g (исходный образец)	0	0	1.88	0.84
94	34	$1 \cdot 10^5$	1.98	0.88
95	34	$2 \cdot 10^5$	2.09	0.93
87	34	$4 \cdot 10^5$	2.18	0.97
54	34	$6 \cdot 10^5$	2.22	1.00
58	34	$1 \cdot 10^6$	2.22	1.00
57	34	$5 \cdot 10^6$	2.22	1.00
6	34	$1 \cdot 10^7$	2.22	1.00
17	0	0	1.89	0.85
26	36 h (предел усталости)	$1 \cdot 10^5$	2.01	0.89

a № образца	b Напряжение цикла, кг/мм²	c Число циклов	d $B_{(220)}$, мм	e $B_{(110)}$, мм
41	36	$2 \cdot 10^5$	2.12	0.94
84	36	$4 \cdot 10^5$	2.21	1.00
36	36	$6 \cdot 10^5$	2.26	1.03
73	36	$1 \cdot 10^6$	2.22	1.03
79	36	$5 \cdot 10^6$	2.22	1.03
22	36	$1 \cdot 10^7$	2.26	1.03
3	0	0	1.88	0.81
62	38	$1 \cdot 10^5$	2.05	0.92
67	38	$2 \cdot 10^5$	2.19	0.99
65	38	$4 \cdot 10^5$	2.32	1.07
52	38	$6 \cdot 10^5$	2.32	1.07
48	38	$1 \cdot 10^6$	2.32	1.07
49	38	$5 \cdot 10^6$	2.32	1.07
	i Излом			

Legend: a) No. of sample; b) Cyclic stress, kg/mm^2; c) Number of cycles; d) $B_{(220)}$, mm; e) $B_{(110)}$, mm; f) (standard sample); g) (initial sample); h) (fatigue limit); i) Break.

By the method of harmonic analysis and the integral method, it turned out to be possible to determine the initial magnitude of blocks to be 1.5 x 10^{-5} cm. The process of alternating loading fragmentation of the blocks starts at the first stages of the test.

After achievement of the minimum value, equal to 4.0×10^{-6} cm (Fig. 1), change in the blocks ceases and their magnitude remains constant to the end of the test at 1×10^{7} cycles. At a load above the fatigue limit, fragmentation of the blocks ceases before 4×10^{5} cycles and attains a smaller value than at a load below or at the fatigue limit at 6×10^{5} cycles.

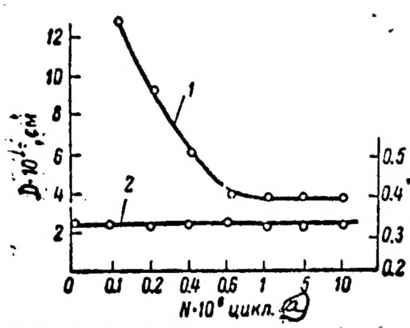

Fig. 1. Dependence of blocks (1) and micro-distortions (2) on number of cycles of load. Magnitude of blocks 10^{-5} cm, σ = 36 kg/ mm^2. a. cycles. [Exponent of 10 on the ordinate illegible]

Analysis of the results of investigation of 40X steel samples having initial magnitude of blocks of the order 10^{-5} cm, shows that a line broadening occurs chiefly as the result of fragmentation of the blocks.

The magnitude of the blocks is changed almost by an order of magnitude: 1.5×10^{-5}--3.5×10^{-6} cm.

In Table 2, results are given of measurements of the widths of the lines (220) and (110) for samples having initial magnitude of blocks of order 10^{-3} cm. The widths are given for loads below the fatigue limit by 2 kg/mm^2, on the fatigue limit and at 2 kg/mm^2 above this limit.

The change in line width of (220) for a load 2 kg/mm^2 above the fatigue limit is 10% more than at a load equal to the fatigue limit and below it (Fig. 2). The change of the line width (220) as compared with the line width of a standard sample of 40X steel is insignificant (20--30%).

Table 2

Magnitude of blocks of order of 10^{-3} cm

a № образца	b Напряжение цикла, кг/мм²	c Число циклов	d $B_{(220)}$, мм	e $B_{(110)}$, мм	a № образца	b Напряжение цикла, кг/мм²	c Число циклов	d $B_{(220)}$, мм	e $B_{(110)}$, мм
10 (f стандартный образец)	0	0	1.23	0.75	4	26.5	$4 \cdot 10^5$	1.42	0.81
					18	26.5	$6 \cdot 10^5$	1.47	0.83
					82	26.5 (предел g усталости)	$2 \cdot 10^5$	1.38	0.79
17	24.5	$1 \cdot 10^5$	1.31	0.77					
24	24.5	$2 \cdot 10^5$	1.38	0.79					
30	24.5	$4 \cdot 10^5$	1.42	0.81	4	26.5	$4 \cdot 10^5$	1.42	0.81
1	24.5	$6 \cdot 10^5$	1.47	0.83	18	26.5	$6 \cdot 10^5$	1.47	0.88
45	24.5	$1 \cdot 10^6$	1.47	0.83	83	26.5	$1 \cdot 10^6$	1.47	0.83
46	24.5	$5 \cdot 10^6$	1.46	0.82	93	26.5	$5 \cdot 10^6$	1.48	0.83
8	24.5	$1 \cdot 10^7$	1.48	0.83	77	26.5	$1 \cdot 10^7$	1.48	0.84
21 (f стандартный образец)	0	0	1.23	0.75	14 (f стандартный образец)	0	0	1.23	0.75
1	g 26.5 (предел усталости)	$1 \cdot 10^5$	1.31	0.77	71	28.5	$1 \cdot 10^5$	1.35	0.79
					53	28.5	$2 \cdot 10^5$	1.48	0.82
					92	28.5	$4 \cdot 10^5$	1.62	0.85
15	26.5 (предел усталости)	$2 \cdot 10^5$	1.38	0.79	88	28.5	$6 \cdot 10^5$	1.63	0.84
					51	28.5	$1 \cdot 10^6$	1.63	0.85
					13	28.5	$5 \cdot 10^6$	1.63	0.85
					37	28.5	$6 \cdot 10^6$	1.63	0.85
						h Излом			

Legend: a) No. of samples; b) Cyclic stress, kg/mm²; c) Number of cycles; d) $B_{(220)}$, mm; e) $B_{(110)}$, mm; f) (standard sample); g) (fatigue limit); h) Break.

The magnitude of blocks determined by formula of Selyakov--Scheurer (for that, it was necessary to make the assumption that true line broadening β occurs chiefly as the result of the magnitude of the blocks), decreases during the alternating loading at all the loads considered. Since the change in width line $B_{(220)}$ during fatigue testing of samples with initial blocks of 10^{-3} cm is insignificant as compared with line width of standard sample $b_{(220)}$, then the true line width β (220) was determined by the formula $\beta = \sqrt{B^2 - b^2}$.

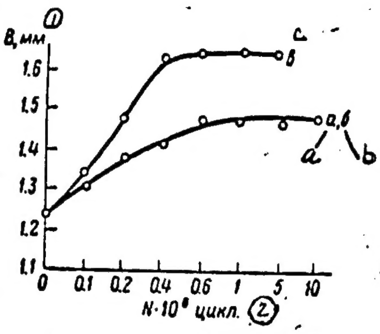

Fig. 2. Dependence of line width (220) on the number of cycles. Magnitude of blOcks 10^{-3}cm
a-- σ = 23.5 kg/mm^2; b-- σ = 25.5 kg/mm^2; σ = 27.5 kg/mm^2.
1. B,mm; 2. cycles

The correctness of the assumption on the absence of development of micro-distortions during alternating loading of 40X steel having an initial magnitude of blocks of the order of 10^{-3} cm, was checked by x-ray photographs obtained by the photomethod from a non-rotating sample without rotation of the cassette. In comparison of the x-ray photograph obtained from sample, through 1 x 10^5 cycles of alternating loading, with x-ray photograph from initial sample, it is clear that separate reflexes after first cycles of test are eroded and merge into a solid ring that is proof of the intense fragmentation and disorientation of the initial blocks. In the presence of some micro-distortions only, the separate reflexes would be eroded in the radial direction.

At 6 x 10^5 cycles of alternating loading, it seems then, by the broadening of lines (220) and (110), to be possible to determine the magnitude of the blocks and micro-distortions separately. The last ones turned out to be significant, less 0.1 x 10^{-3}.

The magnitude of blocks 10^{-2} — 10^{-4} cm is usually determined by an increase of intensity of the fronts of the lines with small indices at the expense of decrease of the influence of the primary extraction during fragmentation of blocks [2]. Inasmuch as at initial cycles of

1 x 10^5 for all loads considered broadening of lines is insignificant, then the dimensions of blocks are less than 1 x 10^{-4} cm. Therefore, primary and secondary extinction, [3], can have an influence on the line intensities which explains the fact that the dimensions of blocks, determined from the coefficient of primary extinction and by broadening of lines for the same samples, differ in order of magnitude. Since micro-distortion is absent during loading of samples having initial magnitude of blocks 10^{-3} cm, then the magnitude of the blocks for all cycles of test was determined by the Selyakov formula to reveal the alternating character of the development of fragmentation of blocks in 40X steel subjected to fatigue.

During alternating loading of 40X steel, the fragmentation of the blocks (Fig. 3) continues up to a definite number of cycles, and its further development is not observed up to the end of tests of 1 x 10^7 cycles. For a load 2 kg/mm^2 higher than the fatigue limit, the

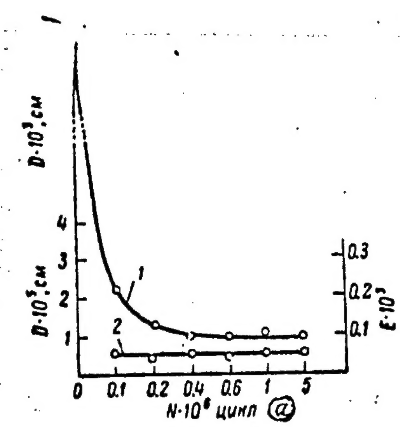

Fig. 3. Dependence of blocks (1) and micro-distortions (2) on the number of cycles of load. Magnitude of blocks 10^{-3} cm, $\sigma = 25.5$ kg/mm^2.

a.. cycles

development of fragmentation of blocks, just as for initial blocks 1 x 10^{-5} cm, is finished earlier (4 x 10^5 cycles) than at loads 2 kg/mm^2 less than the fatigue limit and on fatigue limit (6 x 10^5 cycles). The limiting value of blocks at a load higher than the fatigue limit is less than 1 x 10^{-5} cm, and for loads 2 kg/mm^2 below the fatigue limit and at the fatigue limit--more than 1.3 x 10^{-5} cm, i.e., the limiting value of blocks at fragmentation in process of fatigue of 40X steel

depends on the applied stress. This dependence is clearly expressed for large block initial samples.

Thus, the mechanism of the process of fatigue of 40X steel having initial magnitude of blocks of the order of 10^{-3} cm, just as for initial blocks with dimensions of the order of 10^{-5} cm, is fragmentation of blocks, but for initial blocks with dimensions of the order of 10^{-3} cm, a decrease in the magnitude of blocks occurs by two orders, 10^{-3}--10^{-5} cm, and for initial blocks with dimensions of the order of 10^{-5} cm, by one order: 10^{-5}--10^{-6} cm. Consequently, in large block samples, the fragmentation of the blocks in 40X steel fatigue tested, takes place more intensely than in small-block samples. However, in large block samples fatigue tested, as a result of development of fragmentation, the limiting dimension of blocks is 1×10^{-5} cm more than in small-block samples, in which the limiting dimension of the blocks decreases to 3.5×10^{-6} cm. This is one of the causes of increase of the fatigue limit of 40X steel by approximately 30% for samples having initial magnitude of blocks of the order of 10^{-5} cm, as compared with samples having initial magnitude of blocks of the order of 10^{-3} cm.

Investigation of the mechanism of fatigue of 40X steel by interference line broadening, which is produced by the development of effects of the second kind, shows that the change of thin internal structure occurs basically as the result of a decrease of the dimensions of the blocks of mosaic and their disorientation (this is a confirmation of the fact that in the fatigue process texture cannot appear. Microdistortions connected with change in the interplanar distances are not developed inside the blocks. They are insignificant and are identical for all loads considered.

The development of process of fragmentation of blocks occurs in the early stages of the test, both at stresses above the fatigue limit, and in the range of safe loads. Crushing of crystal blocks occurs for a definite number of cycles of alternating load, and then their magnitude is not changed up to the end of the test. More intense fragmentation of blocks occurs in large block samples. The limiting dimension of the crystal blocks depends on the initial crystal structure of the investigated metal and, in very small measure, on the applied stress (a change in the limiting value of the blocks is observed at a load above the fatigue limit where it is clearly expressed for large block samples).

Changes in the interference picture for alternating loading of the 40X steel are observed not only in line broadening, but also in the change of intensity of the latter.

The intensity of the lines of the x-ray photograph in the fatigue process can be changed depending upon two causes: 1) from fragmentation of the crystal blocks which leads to a decrease in the primary extinction and, consequently, to intensification of the lines of the x-ray photograph; 2) from the appearance of elementary distortions in the lattice (stresses of the third kind).

The influence of the texture during fatigue test of annealed samples is eliminated as a result of the intense development of the process of fragmentation of the blocks, their disorientation, and the alternating character of the deformation. Furthermore, absence of any influence of the texture on intensity of lines (220) and (110) was controlled by the x-ray photographs obtained by photomethod from a non-rotating sample, without rotation of the cassette, in that same radiation which was used in the ionization method.

The integral intensity was calculated by means of measurement of the area of the interference maxima. In all cases, the ratio of the integral intensity of the interference line of the investigated sample and the integral line strength of the standard sample, was taken into account.

In Fig. 4 is shown the dependence of the intensity of lines (110), (200), (211) and (220) on number of cycles of the alternating load, corresponding to loads equal to fatigue limit and to 2 kg/mm^2 above it. During load at 2 kg/mm^2 below the fatigue limit no changes occur in the values of the intensity of the above-mentioned lines. At a load equal to fatigue limit and to 2 kg/mm^2 above it, there is a regular decrease in intensity of all the lines.

The dependence of the intensity of lines (110), (200), (211), (220) on the number of cycles of alternating load of 40X steel for those same three above-mentioned loads is represented in Fig. 5.

In the initial test period, an increase of intensity is observed for all lines, both at a load 2 kg/mm^2 above the fatigue limit and at the fatigue limit, and also at 2 kg/mm^2 below it. This intensity increase is explained by the fact that for all the above loads fragmentation of the blocks and their disorientation take place.

Fragmentation of crystal blocks brings about a decrease in influence of primary extinction and, consequently, an increase in the intensity of the first lines of the x-ray photograph. As a consequence of the primary extinction, the intensity of the lines in initial blocks of the dimension 10^{-3} cm was lowered.

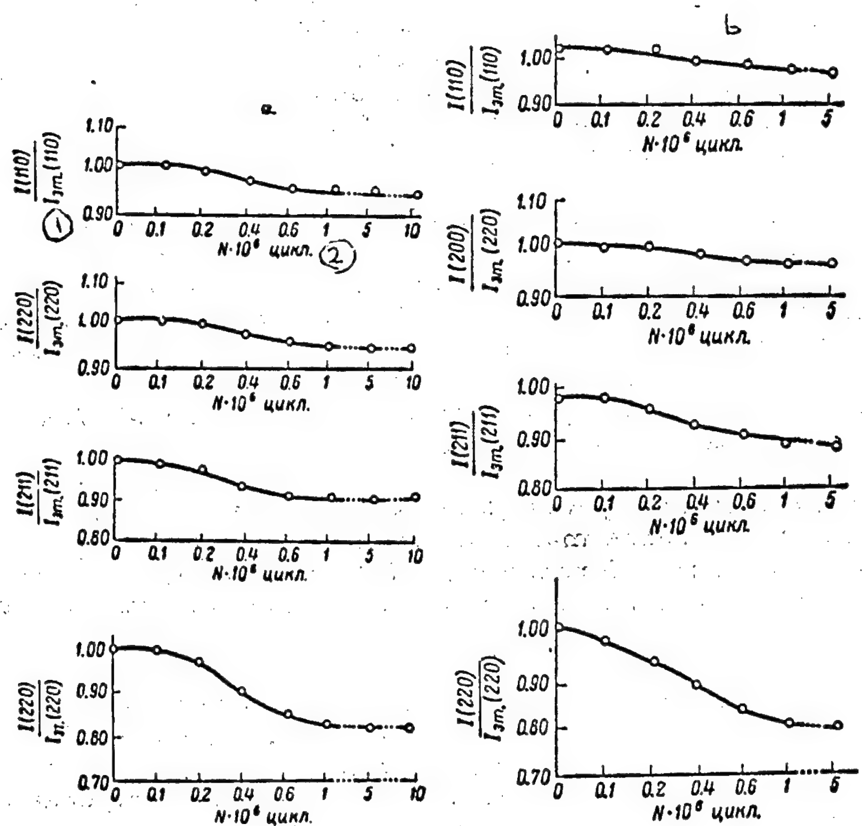

Fig. 4. Dependence of the intensity of the interference lines on the number of cycles of alternating load. Magnitude of blocks 10^{-5} cm.

a -- $\sigma = 36$ kg/mm^2; b -- $\sigma = 38$ kg/mm^2.

1. I_{st} ; 2. N x 10^6 cycles.

For a load 2 kg/mm^2 lower than the fatigue limit no decrease in intensity of lines at the expense of elementary distortions is observed. But at a load before fatigue limit and at 2 kg/mm^2 above it (picture of a change in intensity on the number of cycles of load with these two loads identical, a decrease of intensity of the lines takes place, increasing with the order of the reflection.

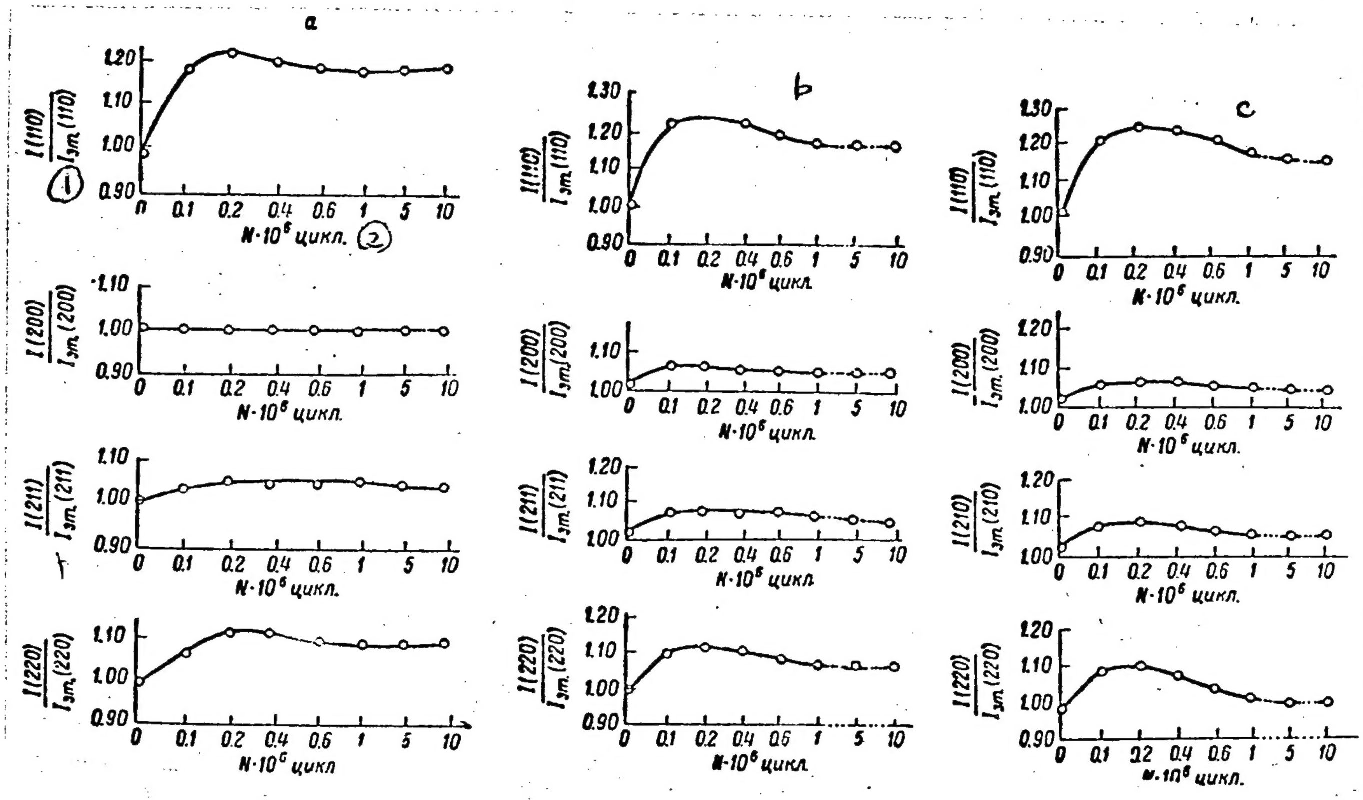

Fig. 5. Dependence of the intensity of the interference lines on the number of cycles of alternating load. Magnitude of blocks 10^{-3} cm.

a -- $\sigma = 23.5$ kg/mm^2; b -- $\sigma = 25.5$ kg/mm^2; c -- $\sigma = 27.5$ kg/mm^2.

1. I_{st} ; 2. N x 10^6 cycles.

Consequently, for 40X steel having initial blocks with dimensions of the order 10^{-3} cm, just as for initial blocks of the order 10^{-5} cm, a decrease in intensity of the interference lines occurs discretely in the transition from the safe interval of stress to the dangerous one, which, it can be assumed, is produced by the development of elementary distortions (stresses of the third kind).

A decrease in intensity in the test of the fatigue of samples having an initial large-block structure is weakly expressed. In these samples, the influence of extinction on the line strength is large as compared with the decrease in the intensity as a result of elementary distortions. Therefore, by skipping the initial period of test in initial large-block samples, it is possible not to observe any further decrease in intensity (after first increase).

Distortions of crystal lattices, revealed by X-ray methods in annealed 40X steels subjected to an alternating deformation, can be explained by proceeding from the dislocation model. The density of dislocations calculated by the formula of Williamson and Smelman [4] is increased according to our experimental data. For large-block samples with initial dimension of blocks 10^{-5} cm this density is increased to 10^{12} cm^{-2}.

The increase in the dislocation density during alternating deformation and strengthening of the material at comparatively low loads equal to the elastic limit, can be explained in the following way. Softening in the change of sign of the load does not occur since in the movement of the dislocations in region of crossing of two sliding surfaces, "sedentary" dislocations are formed which create Lomer-Cottrell obstacles and retard the advance of other dislocations, i. e., the movement of subsequent plastic flow. The sources generate dislocations of one sign, which, upon colliding, move to the boundaries of blocks, accumulate there and distort them. Fragmentation of blocks occurs, as well as an increase in the angle of the mosaic character, up to some definite value.

In steel alloys, during movement of dislocations, foreign atoms are attracted and a Cottrell cloud is formed: these are "sedentary" dislocations. During application of the corresponding stress, which should be larger than the stress necessary for advance of the dislocations, avalanche develops chaotically located inside the mosaic blocks. For concentration of the stress on L (the length between dislocations) transition of atoms through the potential barrier is possible which will bring about their displacement to distances not smaller than half of the interatomic distance. Such atomic arrangement

will produce a weakening of the intensity which is strongly evident on the lines of highest orders, which is in some measure analogous to the appearance of thermal vibrations. Such distortions of the crystal line lattice can be related to the so-called stresses of the third kind.

CONCLUSIONS

1. During fatigue testing of 40X steel, fragmentation of crystal blocks occurs during stresses both above and at and below the limit.

2. Development of micro-distortions does not occur.

3. With increase in number of cycles of alternation of the load, development of process of fragmentation of the blocks first occurs; then, after a definite number of cycles of loading and up to the end of the test, the magnitude of the blocks is not changed.

4. In large-block samples, the process of fragmentation of the blocks is more intensely developed than in small-block, but the limiting dimension of blocks in the process of fatigue testing of large-block initial samples is larger than for samples having small-block initial structure.

5. The magnitude of the characteristics of effects of the second kind can depend on the applied stress, but for loads lower or higher than some definite value development or further increase of effects of the second kind does not generally occur.

6. The decrease in the intensity of the x-ray interferences has a discrete character in the transition from safe load to a dangerous one. In fatigue testing of samples having initial large-block structure, the decrease of intensity produced by the development of elementary distortions is weakly expressed. In these samples, the influence of extinction on the intensity of the lines is more significant than the decrease of intensity at the expense of elementary distortions.

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